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MODE USAGE IN AUTOMATED COCKPITS: SOME INITIAL OBSERVATIONS

Asaf Degani
San Jose State University
San Jose, CA
and NASA Ames Research Center
Moffett Field, CA

Michael Shafto
NASA Ames Research Center
Moffett Field, CA

Alex Kirlik
Georgia Institute of Technology
Atlanta, GA

ABSTRACT

Mode confusion is increasingly becoming a significant contributor to accidents and incidents involving highly automated airliners; in the last seven years there have been four airline accidents in which mode problems were present. This paper provides some initial observations about modes and how pilots use them. The authors define the terms "mode," "mode transitions," "mode configurations," and propose a framework for describing and classifying modes. Preliminary results from a field study that documented mode usage in "Glass Cockpit" aircraft are presented. The data were collected during 30 flights onboard Boeing 757/767-type aircraft. Summary of the data depicts the various paths pilots use in transitioning from one mode to another. Analysis of the data suggest that these mode transitions are influenced by changes in aircraft altitude as well as by two factors in the operational environment: the type of air traffic control facility supervising the flight, and the type of instruction (clearance) issued.

INTRODUCTION

Modes are found in almost every supervisory control system. Yet, it appears that in some highly automated systems, mode confusion is a trigger for many accidents and incidents. Modes, as a method for human-automation interaction, are now recognized as an operational problem by both operators and manufacturers of these systems (Aviation Week and Space Technology, 1995a, 1995b). But just what are modes? How are they used by operators in supervisory control systems? This paper attempts to provide some initial insights into these two questions.

The first part of the paper discusses mode usage from several aspects: (1) an historical perspective, (2) symptoms of mode problems, (3) definitions, and (4) a framework for describing and classifying modes. In particular, the discussion focuses on mode transitions—a critical aspect of user interaction with a modal system. The second part of the paper discusses preliminary results from a field study documenting how operators transition between the various modes of operation, and what factors prompt these transitions. The discussion is set in the context of pilots using the automatic flight control system of a modern "glass cockpit" aircraft.

Historical perspective

Historically, the issue of modes in human computer interaction emerged as more and more functions were added to early word processors, and yet the size of the interface (e.g., number of function keys, screen area, etc.) stayed constant. One solution was to use the same key to engage several commands; this was implemented by providing the user with some mechanism to switch the application from one mode to another. Depending on the mode, hitting the same key would execute different commands. In this paper the term f*ormat/data-entry* modes is used to describe this type of mode implementation. For example, the vi text editor has two modes of operation: "Command" and "Insert." In "Command" mode, pressing the *x* key will delete a character; in "Insert" mode, this action will write the letter "x" on the screen.

Users of these early applications, however, were not always happy with such mode implementations: errors, or *mode-errors*, as these were termed by Norman (1981), caused confusion and frustration (Lewis, and Norman, 1983). Tesler (1981) captured this growing frustration in his influential article in *Byte* magazine and his pointed cry: "don't mode me in." Research on modes in the human computer interaction literature has mostly focused on various implementations for the mode switching mechanism (Monk, 1986; Sellen, Kurtenbach, and Buxton, 1992; Thimbleby, 1982). The problem, nevertheless, has not disappeared: efficient modes and switching mechanisms continues to be part of any human-computer interface.

The same growing pains are now shared by designers and operators of supervisory control systems (*Aviation Week and Space Technology*, 1995a; Woods, Johannesen, Cook, and Sarter, 1993). Since most supervisory control systems are managed via a computer, format/data-entry modes for input of information and display switching are heavily used. But in most supervisory control systems there is also another type of mode: one that is used for controlling the process. This unique type of mode is the method used for engaging various control behaviors (e.g., reverse/drive gears in a car). In this paper, the term *control* modes is used to describe this type of implementation.

Symptoms of mode problems

In the last seven years, there have been four fatal airline accidents in which mode problems were cited. In the first, an Air France Airbus A-320 crashed in Habersheim-Mullhouse Airport, France, following a low altitude fly-by (Ministry of Transport, 1990). The crew, flying close to the ground, engaged a pitch mode that provides relatively slow thrust response to throttle movement. In the second accident, an Indian Airlines A-320 crashed during a visual approach to Bangalore Airport, India (Gopal and Rao, 1991). The crew, intentionally or unintentionally, engaged a pitch mode in a way that provided no speed or altitude protection. In the third accident, an Air Inter A-320 crashed during a nighttime approach into Strasbourg-Entzheim Airport, France. The accident report suggests that the crew may have mistakenly engaged the wrong mode for the situation at hand (*Aviation Week and Space Technology*, 1994a). In the fourth accident, a China Airlines A-300/600 crashed during an approach into Nagoya International Airport, Japan. The crew, unintentionally or intentionally, engaged a mode that commanded climb with full thrust, and at the same time manually pushed the control wheel down in order to prevent the aircraft from climbing. In a conflict between manual versus autopilot commands, the aircraft achieved an extreme pitch attitude of 36 degrees with decaying airspeed, rolled to the right, and crashed (*Aviation Week and Space Technology*, 1994b).

MODES

Before studying mode usage, it seems important to describe what are modes and what types of human-machine interaction they foster. Unfortunately, in the context of human-machine systems, no common terminology for describing modes is available. The following discussion suggests a terminology and proposes a framework for classifying different types of modes.

Terminology and definitions

A mode is defined here as a *manner of behaving*. This general definition satisfies the use of the term within any system, may it be behavioral, social, organizational, or a hardware/software system (Ashby, 1956; Goldberg and Goldberg, 1991; Nadler, 1989; Perrow, 1986). Taken as a whole, a system can have several ways of behaving; but at any point in time only a single mode can be active. If each mode behavior can be captured as a vector of several operands (e.g., c, d, d, b), then the transition table in Figure 1 can describe this modal system.

↓	a	b	c	d
M_1	c	d	d	b
M_2	b	a	d	c

Figure 1. Modal system

For a given system, M_1 corresponds to a mode-switch set to position 1, and M_2 to position 2. Mode transition, or the change of M's subscript from 1 to 2, is a transformation from one manner of behaving to another (Ashby, 1956). The machine's overall behavior is a combination of its various mode behaviors and transitions.

The human operator interacts with the machine via its modes. Problems in the human-machine interaction, or in particular mode confusion, usually result from misidentification of the machine's behavior—its mode behavior and its mode transitions. Such mode confusion may lead to error. Some of these mode errors may occur when the user takes some action (e.g., issues a command) believing that the machine is in one mode, when in fact it is in another (Norman 1983). Since the machine's behavior changes as a result of a mode transitions, it is not surprising that such transitions are a critical ingredient of mode confusion and subsequent mode errors.

Mode transition

Ashby (1956) describes a system that exhibits various manners of behavior as a machine with input. This input is the determining factor in making the transition from one mode to the next. In the context of modes in human-machine systems, three types of inputs may be used: manual, automatic, and automatic/manual. In a *manual* input, or a manual mode transition, the user directly engages the mode (and consequently disengages another). This is the most commonly used mode type (e.g., modes on an electronic watch, or a text editor's insert/replace modes). In an a*utomatic* input, or a automatic mode transition, a controller (another machine) initiates the transition. This type of mode transition is mostly used in fully automatic systems (e.g., an anti-lock braking system in a modern car). In an *automatic/manual* mode transition, either the human or the machine initiates the transition. This kind of transition is used in quite a few systems and appliances (e.g., a microwave can switch from "Cook" mode to "Idle" mode either automatically or when the user intervenes manually).

Mode classification

Earlier we distinguished between two primary mode functions: *format/data-entry* and *control*. These two types of functions, combined with the three types of inputs (*manual*, *automatic*, and *automatic/manual*) form a matrix that can be represented in a 2 x 3 table. This table can be used for classifying modes (Figure 2).

	Manual	Auto/Manual	Automatic
Format/ Data-entry	*Many*	*Few*	*Rare*
Control	*Many*	*Many*	*Few*

Figure 2. Mode classification

This proposed classification is not always crisp. Some may argue that the term "control" can be applied to both writing a document on a word processor and flying an airplane. The various systems that we surveyed had modes that fell naturally into one of the cells in the table. Only *format/data-entry* modes that transition *automatically* were a rarity. Nevertheless, some do exist—certain ATM machines automatically switch to another format (or mode) once the expected entry is typed.

Mode configuration

An additional input to any modal system are the parameters, or target values, that the machine has to maintain (Lambergts, 1983). In other words, these target values constrain mode behavior. For example, the pitch component of an automated flight control system has several modes: "Vertical Speed," "Vertical Navigation," and others (Figure 3). Mode transitions, depicted by the arrow on the top, can occur either manually, automatic/manually, or entirely automatically. Once a mode is active, it will operate according to its characteristic behavior while attempting to maintain these target values. A target value, say airspeed, may come from various sources: if the "Vertical Speed" mode is active, the target value is obtained from the mode control panel; if the "Vertical Navigation" mode is active, airspeed target value is obtained from the flight management computer.

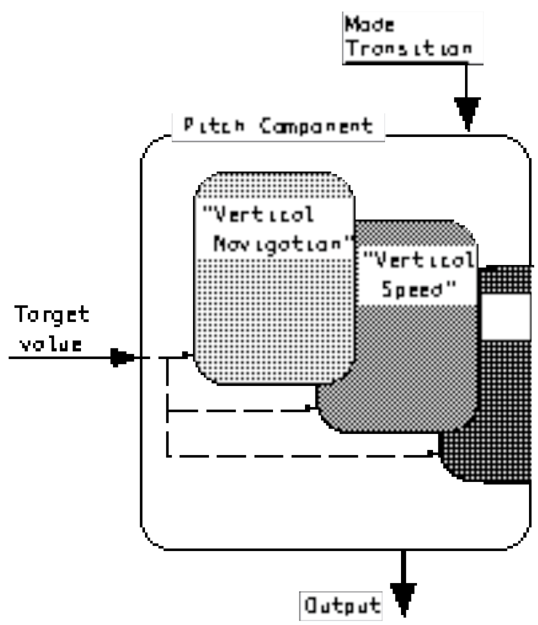

Figure 3. Mode transition, target value, and output

The originator of the target values can be either the pilot or the machine. Continuing the above example, when the "Vertical Speed" mode is active, the pilot (the originator) enters the desired airspeed into the mode control panel; when the "Vertical Navigation" mode is active, the flight management computer (the originator) calculates the most economical airspeed for the particular flight situation.

The pilot, therefore, has several options to control the aircraft: he or she can change the target values of the current mode, or transition to another mode. The term *mode configuration* is used here to describe the type and value of the various target values entered into the machine. For example, a change in mode configuration occurs when the pilot enters a new rate of descent while the "Vertical Speed" mode is active or when the pilot changes the vertical profile while the “Vertical Navigation” mode is active. Over time, the changes in target values define the *mode configuration trajectory*.

A system with several modes

In many complex domains a given system is made up of several sub-systems, or components. Each of these components may have its own set of modes. Therefore, unlike a simple system that may exhibit only one mode at a time, the status of a complex system, with respect to its modes, is a vector of all active modes. Furthermore, since by definition some relationship exists between the components of a system, interactions exist between a mode of one component and a mode of another component. Thus we propose here several definitions and terms for describing human-machine interactions via modes. In the following sections, we use these terms to describe how pilots interact with the automated flight control system of a modern airliner.

TASK DEMANDS AND MODES

The various accidents mentioned is section 1.2, as well as hundreds of mode-related incidents (ASRS, 1991; *Aviation Week and Space Technology*, 1995a), suggest a link between mode design/usage and operational problems (Sarter and Woods, 1994). The authors of this paper hypothesize that some of these problems stem from the mismatch between the demands placed on the human supervisor and the mode structure of the system. The term *mode structure* is used here to describe the hierarchy of modes in a system, the transitions among modes, and the transformations that occur from one mode to another. In the context of a complex system with several components, mode structure also signifies the interactions between the modes of one component and the modes of another component.

On the one hand, the pilot has formulated a set of goals that he or she attempts to accomplish in a logical, efficient, and safe manner. On the other hand, the system has a predetermined set of methods, or modes, that are available for controlling the system. Various paths exist for transitioning between these modes. If and when task demands do not match the mode structure of the system, mode confusion and unwanted results may ensue. This link is only amplified when the operating environment as well as the system are highly dynamic: frequent changes in environmental demands (e.g., ATC clearances) and aircraft situation (e.g., imminent stall) require frequent mode transitions.

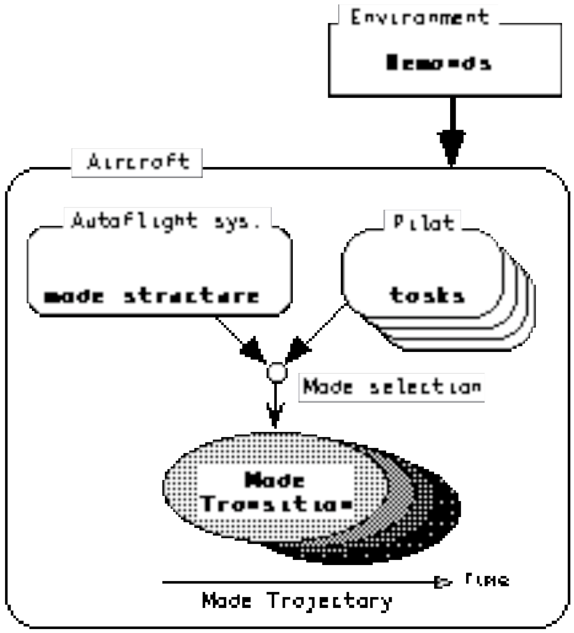

Figure 4. Mode trajectory

The mode structure of the system, the task demands, and the pilot's goals all combine to produce mode selection. This can be recorded as a mode transition from the previous mode to the current mode, and over time as a continuum of mode transitions that forms a mode trajectory (Figure 4). Problems in identifying the automatic flight control system's behavior appear to be a critical component in many accidents and incidents. It appears reasonable, therefore, that one approach for studying mode usage is to document and understand mode trajectories.

METHOD

Mode transition data was collected by an observer onboard an airliner during the climb-to-cruise and descent-to-land phases of a flight. The observations were conducted during two typical trips, each comprised of three flights. Each of the two trips was observed five times. This design of experiment yielded 30 flights (2*3*5). Subjects were airline pilots from a major US carrier, flying regular revenue flights in either the Boeing B-757 or B-767—both modern "glass cockpit" aircraft equipped with an automatic flight control system (AFCS).

The AFCS is composed of three major components: autopilot, autothrottle, and flight management computer (FMC). Sitting in the jumpseat, the observer recorded the following variables: changes in pitch and roll modes, thrust modes, FMC modes, as well as whether the autopilot, flight-director, and autothrottle were "On" or "Off." Other information such as aircraft altitude, distance/bearing from airport, weather, air traffic control (ATC) clearances, and the type of ATC facility supervising the flight were also recorded. Crew information, such as rank (captain, first officer) and duty (pilot-flying, pilot-not-flying) were collected. The dataset analyzed here contained 30 flights which amounted to some 700 records of both mode changes and mode configuration changes.

ANALYSIS

The objective of this analysis was twofold: (1) to describe mode transitions and the frequency of occupying a certain mode (mode occupancy), and (2) to identify possible factors that prompt these mode transitions. In particular, the authors hypothesized that one of the strategies that flight crews use to combat complexity of the system (e.g., its mode structure and mode behaviors) is by using a small subset of all possible modes, and that these strategies are influenced by task demands coming from the operational environment. Of the some 700 records in the dataset, only those that documented mode transitions were included (mode configuration were excluded). The reduced dataset contained 291 records.

Mode occupancy and transition

Mode occupancy. The various pitch and roll modes of the automatic flight control system (AFCS) are represented in a 5*8 table (Figure 5). On the horizontal legend (columns) are listed the five modes of the roll component; on the vertical legend (rows) are listed the eight modes of the pitch component. Since the status of the AFCS in this analysis is described as a vector of both pitch and roll modes, each cell in the table indicates such a combination. On the Northwest corner of the table, the combination of “Manual Roll” mode and “Manual Pitch” mode indicates a situation in which the pilot is flying manually: autopilot and autothrottle are disengaged, and he or she is flying without reference to the flight director guidance. On the Southeast corner of the table, the combination of “Lateral navigation” mode and “Vertical Navigation” mode indicates a situation in which the aircraft is flown fully automatic. The numerical value in each cell indicates the occupancy frequency.

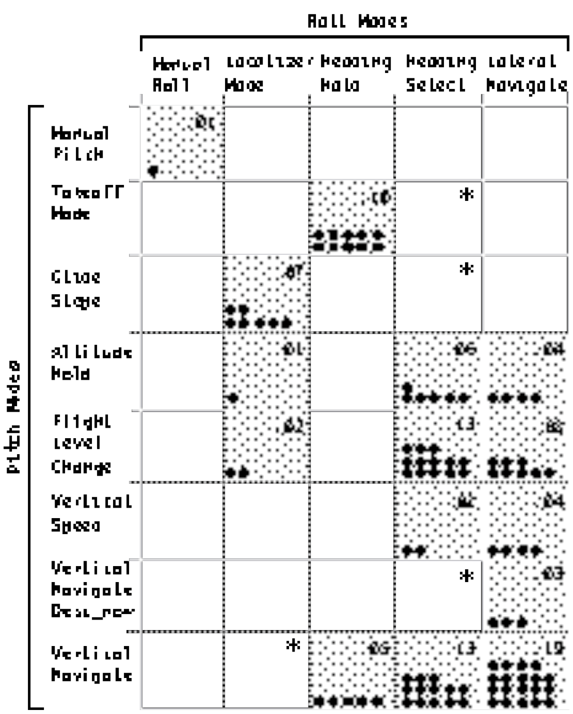

Figure 5. Mode occupancy. (* indicates 0 < occupancy < 0.01).

Two observations can be made from Figure 5:

(1) only some of the pitch/roll mode combinations are occupied, and (2) heavy occupancy is either associated with a procedure (e.g., using "Takeoff Mode"/Heading Hold" during takeoff is a standard operating procedure in this airline), or a preferred mode combination (e.g., "Heading Select" and "Flight Level Change").

Mode transitions. Figure 6 depicts mode transitions among the pitch/roll mode combinations (only those that were shaded in Figure 5). The transitions between these mode combinations shows the possible paths that pilots use from takeoff to touchdown. Broken lines shows the initial transition from *start of flight* to "Takeoff Mode"/"Heading Hold" mode combination as well as the final transitions from "Flight Level Change"/"Localizer Mode," "Manual Pitch"/"Manual Roll," and "Glide Slope"/"Localizer mode" to *touchdown*.

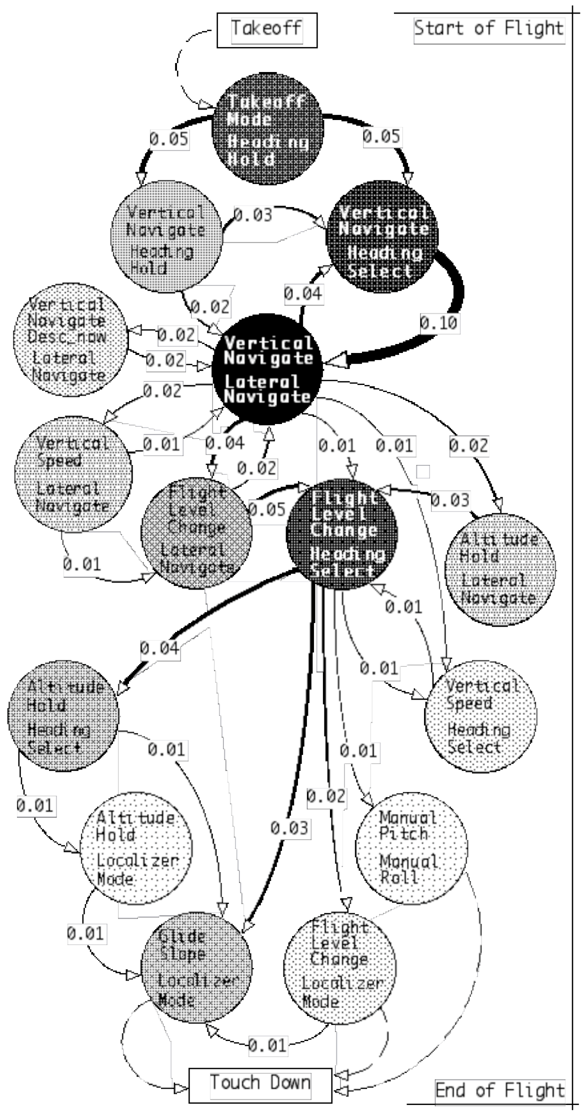

Figure 6. Mode transitions. (dark shading indicates high occupancy).

Dark shading indicates the heavy occupancy of the “Lateral navigation”/“Vertical Navigation” and the “Flight Level Change”/“Heading Select” mode combinations; both are pivots for transitioning to other modes combinations. As a unit, the diagram shows how pilots traverse within the mode structure of the AFCS.

Factors influencing mode transition

The previous section summarized and depicted the mode transition in the AFCS. The current section attempts to identify some of the factors that prompted such transitions by using two statistical analysis procedures. The data collected during the flights poses some challenges for such analysis, since the values are mostly discrete and the status of the AFCS is a vector of several modes. Using indicator variables, the discrete data were coded numerically. For example, there were 11 types of ATC clearances; this required 10 indicator variables for coding. A similar coding scheme was used for all other discrete variables. Our analysis approach was to employ two types of procedures in order to identify the factors that prompted mode transitions: (1) a multivariate regression analysis, and (2) a categorical canonical correlation test. For the regression analysis, mode transitions from the 30 flights were randomly split to two equal size sets: a model building set (15 flights), and a validation (hold out) set (15 flights).

Regression. The purpose of the regression analysis was to obtain the relationship between the active mode combination and the dependent factors (e.g., crew duty, rank, leg, trip, phase of flight, altitude, distance from airport, type of clearance, type of ATC facility, type of aircraft). In order to build the regression model, the vector containing the pitch and roll modes was combined into a single ordinal value (the dependent variable—”Y”). This was done by assigning high values to a combination of pitch and roll modes that were highly automated and low values to a combination of modes that were manual. The criterion for the value assignments was the precision of the mode combination for tracking a predetermined path. The advantage of the regression is its simplicity; the disadvantages are the limits on the amount of raw information that enters the model due to using this composite “Y” variable (Walker and Catrambone, 1993), and the normality assumptions associated with this type of analysis.

The results indicated that 61% of the variance in mode transitions can be explained via three factors: the aircraft altitude, the type of ATC facility supervising the flight, and the type of clearance issued by ATC ($\underline{R}^2$adj.= 0.61, $\underline{p} < 0.001$). Cross-validation of the model on the hold out dataset yielded a comparable fit ($\underline{R}^2$adj.= 0.51, $\underline{p} < 0.001$).

Canonical correlation. This procedure is an extension of the multiple regression approach, in that a vector of dependent variables (pitch and roll indicator variables) is used instead of a single dependent variable. Canonical correlation finds the linear combination of independent variables (altitude, ATC clearance, etc.) and the linear combination of dependent variables (pitch and roll mode indicator variables), such that the correlation between the two linear combinations is maximized (Tatsuoka, 1988). Because of the obvious inapplicability of normal-distribution theory to a mostly discrete dataset, a “Monte-Carlo” randomization procedure (Edgington, 1987) was used to test the significance of the canonical correlation, and a “jackknife” method was used to compute an approximate confidence interval (Efron and Tibshirani, 1993).

The preliminary analysis indicates a high canonical correlation between the linear combination of the dependent set and the linear combination of the independent set ($r = 0.95$, $p < 0.01$ by randomization test; approximate 95% confidence interval = [0.90, 0.99]). The analysis showed that ATC facilities (“Departure,“ “En-route,“ and “Approach“) highly influenced mode transitions. Aircraft altitude had only a moderate influence, and the type of clearance had almost no influence in this analysis. Since canonical correlation allows for a vector of dependent variables (“Y’s”), identification of pitch and roll modes that correlate with the dependent variables was performed. On the pitch modes, “Altitude Hold,” “Flight Level Change,” “Vertical Speed,” and “Vertical Navigation” appear to be highly influenced by the independent set. On the roll modes, only “Lateral Navigation” appears to be influenced; the remaining roll modes showed only moderate relation to the independent set.

CONCLUSIONS

The preliminary analysis discussed here is the result of an observational study. This methodology poses some limitations for identifying cause-effect relationships—mainly that the factors are not directly manipulated by the experimenter (Cook and Campbell, 1979). Bearing in mind this limitation, the initial results presented here suggest the following:

First, within the possible mode space there are certain mode combinations that are frequently used. Pilots use several standard and preferred paths for mode transitions during the progress of the flight. Second, these mode transitions are influenced by the aircraft altitude and two environmental factors: type of ATC clearance, and the type of ATC facility (Approach Control, En Route Control, etc.) providing these clearances. We offer several possible explanations for this.

(1) Altitude is a primary factor with respect to both short term (tactical) and long term (strategic) activity on the flight deck; and therefore, directly or indirectly it influences mode transitions

(2) ATC clearances prompt mode transitions. This comes as no surprise, since modes are a method for executing the tasks directed by ATC

(3) ATC facilities vary in the type and rate of clearances.

For example, ATC controllers in an Approach Control facility issue mostly tactical clearances (e.g., maintain heading of 280 degrees, descend to 6000 feet) at a high frequency while demanding a quick response. In contrast, ATC controllers in En Route Control facility issue mostly strategic clearances (e.g., a complete route of flight between several waypoints). Evidence on the influence of both ATC Facility and clearance type on pilots’ mode engagement was also found by Casner (in press).

Taken as a whole, these preliminary findings point to the important relationship between the mode structure of the automated system, and the task demands coming from the operational environment. The result of this relationship, or interaction, are the mode transitions in the system (see Figure 4).

Understanding both the automated system and the operating environment, as well as their interaction, appears valuable for designing new automatic flight control systems. This may be particularly important as future aircraft and the next-generation ATC system are likely to be very different from those of today.

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